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Xingrong Chu[1,a], Lionel Leotoing[2,b], Dominique Guines[2,c], Jun Gao[1,d,*]

[1]School of Mechanical, Electrical & Information Engineering, Shandong University at Weihai, Weihai 264209, China

[2] Université Europeénne de Bretagne, INSA-LGCGM, CS 70839, 20 avenue des Buttes de Coesmës, 35708 Rennes Cedex 7, France

[a]email: chuxingrong@gmail.com, [b]email: lionel.leotoing@insa-rennes.fr

[c]email: dominique.guines@insa-rennes.fr, [d]email: shdgj@sdu.edu.cn

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Abstract. The accuracy of simulation result depends greatly on the implemented hardening law. An appropriate hardening model should be able to describe the coupling effects of the strain, strain rate and temperature on the material flow stress. Based on the stress-strain curves obtained from uniaxial tensile tests, two different hardening models (power law and saturation) are proposed to describe AA5086 flow stresses under different temperatures (20, 150 and 200°C) and tensile speeds (1, 10 and 100 mm·s^{-1}). The correlation results are compared to experimental data and the roles of the hardening models in predicting the material flow stress are compared and discussed.

Introduction

Due to environment protection requirements, the innovative lightweight materials, such as aluminum alloys, have been widely adopted in the automotive industry thanks to their low density, comparable strength and stiffness characteristics. The analytical and numerical methods have been proved to be an effective tool to optimize the forming process parameters or to predict the formability of the studied sheet metal. For these innovative lightweight materials, their mechanical behaviours may be considerable different under different forming conditions. Hence, a reliable strain hardening model which can describe the flow stresses of the material over a wide range of temperatures and strain rates is essential in order to get an accurate modeling result.

Over recent years, several constitutive models have been developed for use in computational mechanics. Based on their intrinsic characters, they are classified into two major groups: physical based models and phenomenological models. The former can be applied to wide forming conditions due to their microstructure theory basis. But the great number of parameters to be identified, the complicated equation formulations and the difficulty of being implemented into finite element (FE) codes limit their applications (e.g. Rusinek-Klepaczko [1]). Although the phenomenological models are based on experimental observations, they are widely used thanks to the simplistic expressions, reduced fitting parameters and the facility to be implemented into FE codes. In the sheet metal forming filed, the phenomenological models generally own a multiplicative expression which comprises the strain, strain rate and temperature functions.

In the literature, several works have been published to model the thermo-viscoplastic behaviour of the aluminum alloys. A modified Bergström model was proposed by van den Boogaard and Bolt [2] for describing the flow stresses of AA5754-O under different temperatures (100, 175 and 250°C) and strain rates (0.002, 2 s^{-1}). An extended Bergström model was also adopted by Palumbo and Tricarico [3] to predict the formability of AA5754-O. With this extended model, good correlation between numerical and experimental punch load was obtained. Abedrabbo et al. [4] proposed a modified power law to study the flow stresses of AA3003-H111 at different temperatures (25 - 260°C) and strain rates (0.001, 0.1, 0.05 and 0.08 s^{-1}). This model gives an accurate punch load curves description. The flow stresses of different aluminum alloys (AA6016-T4, AA5182-O) were described by Aretz [5] with the different forms of Voce models. Good correlations were obtained compared to experimental data. The responses of AA5182-O under a wide range of temperatures (23 - 200°C) and strain rates (10^{-4} - 1 s^{-1}) were studied by Khan and Baig [6] with a modified KHL model. A good correlation result was obtained.

In this study, based on the uniaxial tensile test results, two simple and different types of hardening models are modified to correlate the true stress-strain responses of an aluminum alloy AA5086 under different temperatures (20, 150 and 200°C) and tensile speeds (1, 10 and 100 $mm\cdot s^{-1}$). And the roles of the different hardening laws on the description of the material flow stresses are compared and discussed.

Proposed hardening models

1. Experimental equipments

With the designed grip system which allows a predetermined run to get the desired test velocity and the tested specimen as shown in Figure 1, the uniaxial tensile tests of AA5086 under temperatures (20, 150 and 200°C) and tensile speeds (1, 10 and 100 $mm\cdot s^{-1}$), corresponding to the strain rates of 0.02, 0.2 and 2 s^{-1}, were carried out and the flow stresses of AA5086 under the tested conditions were obtained. The experimental results show that the flow stresses of AA5086 are both temperature and strain rate dependent. The material flow stresses increase with the increasing tensile speed and decrease with the increasing forming temperature as presented in Figure 2.

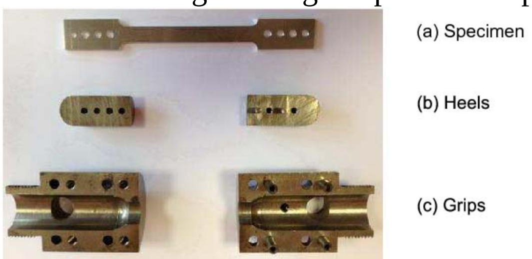


Fig.1. Grip system used in the tensile tests

2. Identification method

Based on the experimental data, taking into the strain rate sensitivity (m) influence with a multiplicative strain rate function, analyzing the evolution of the related parameters with the testing temperature as the similar procedures introduced by Abedrabbo et al. [6], the final proposed hardening models can be obtained. In this work, the fitting parameters are determined with an optimization method through a gradient-based Matlab minimization function.

3. Proposed KHL model

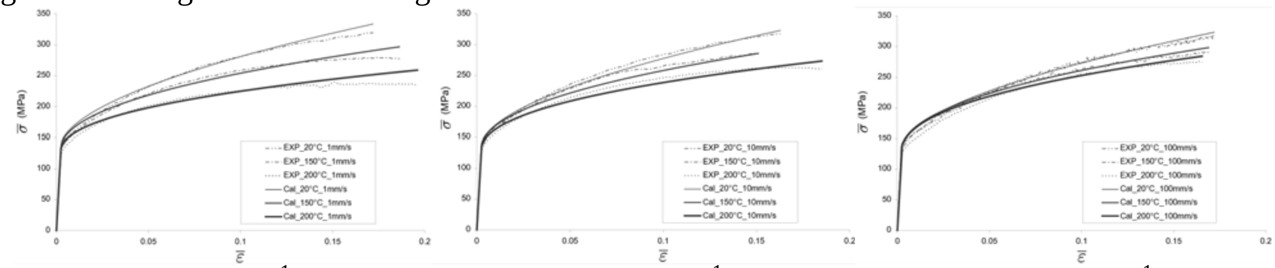
It is found from the experimental results that the initial yield stresses of AA5086 are only dependent on temperature but not on strain-rate, which is commonly verified for aluminum alloys. Based on the values determined from experimental stress-strain curves, the yield stresses of AA5086 can be described by Eq.1.

$$\sigma_0(T) = \left(1 - \frac{T}{T_m}\exp\left(K\left(1 - \frac{T_m}{T}\right)\right)\right)\cdot \sigma_0(T_0) \tag{1}$$

Where $\sigma_0(T_0)$ is the initial yield stress at ambient temperature, K=0.556 is the fitting parameter, T_m = 627°C is the melting temperature. The evolution of the strain hardening and strain rate hardening parameters are analyzed according to the testing temperature. And the proposed KHL model to describe the flow stress of AA5086 is obtained as shown in Eq.2.

$$\overline{\sigma} = \sigma_0(T) + B\left(1 - \frac{\ln \dot{\overline{\varepsilon}}_p}{\ln D_0}\right)^{n_1} \overline{\varepsilon}_p^{\,n_2 - n_3 T}\left(\frac{T_m - T}{T_m - T_r}\right)^{m}\left(\frac{\dot{\overline{\varepsilon}}_p}{\dot{\varepsilon}_0}\right)^{C_0 \exp(C_1 T)} \tag{2}$$

Where T_r = 20°C the reference temperature, B, n_1, n_2, n_3, m, C_0, C_1 are fitting material constants. $\dot{\varepsilon}_0$ = $1s^{-1}$ and D_0 is the maximum strain rate (fixed to 10^6 s^{-1}). The comparison of the flow stresses predicted by the KHL model and the experimental flow stresses are shown in Figure 2 and the identification values are presented in Table 1. As illustrated in Figure 2, despite its simplistic formulation, the proposed KHL model gives a good flow stress description under all the tested forming conditions. Due to its monotonic strain hardening character, the predicted flow stresses all give a little high evaluation at high strain level.



(a) 1 $mm \cdot s^{-1}$ (b) 10 $mm \cdot s^{-1}$ (c) 100 $mm \cdot s^{-1}$

Fig.2. True stress-strain curves of AA5086 and correlation with KHL model under different temperatures and tensile speeds

Table.1. Fitting parameters of the proposed KHL model

B (MPa)	n_1	n_2	n_3 (1/°C)	m	C_0	C_1 (1/°C)
510.4	0.1235	0.5706	0.0007557	1.1345	0.0004105	0.02506

4. Proposed Voce model

A saturation Voce type model is also adopted to correlate the flow stresses of AA5086. The same identified procedure is applied and the final proposed model is obtained as shown in Eq.3. The strain hardening coefficient $K = (K_1 - K_2 T)$ evolves linear with temperature and the strain rate sensitivity index $m = m_0 \exp(m_1 T)$ evolves experimentally as the one observed in KHL model. The identification results are shown in Table 2. The proposed Voce model also gives a good flow stress description for all tested forming conditions. Due to the intrinsic saturation character, the proposed Voce model gives a better flow stress description at high strain level compared to the KHL model as shown in Figure 3. Good correlation results at high strain levels are obtained.

$$\overline{\sigma} = \sigma_0(T) + (K_1 - K_2 T)\left(1 - \exp\left(-(K_3 + K_4 T)\overline{\varepsilon}_p\right)\right)\dot{\overline{\varepsilon}}_p^{\,m_0 \exp(m_1 T)} \tag{3}$$

Table 2 Fitting parameters of the proposed Voce model

K_1 (MPa)	K_2 (MPa/°C)	K_3	K_4 (1/°C)	m_0	m_1 (1/°C)
201.9	0.2457	13.4023	0.04473	0.0001514	0.02965

Discussion

With the proposed hardening models and the identified parameters, the KHL model and the Voce model both give a good flow stress description within the tested strain range for all the forming conditions. Due to the localized phenomenon, the strain level obtained by the tensile test can only up to about 20%. A clear uncertain exists when the identified hardening model is applied to high strain level. While in the sheet forming field, the deformed strain level usually reaches up to about 50%. So it is interesting to compare the flow stresses at high strain level predicted by the two hardening models. With the identified parameters, the extrapolation of the predicted flow stresses with the strain level up to 50% can be determined. As depicted in Figure 4, the two models both give a good flow stress description within the uniaxial tensile strain range, while great discrepancy is observed at high strain level. This difference can be explained by the different strain hardening characters of the two models. And this difference may play an important role in predicting the formability or in optimizing the process parameters in sheet metal forming field. For KHL model, a clearly monotonic flow stress description is observed and a temperature softening effect corresponding to a lower stain hardening rate is found at 200°C compared to the one at 20°C. Due to the saturation character, the Voce model show a saturation stress state at high strain level.

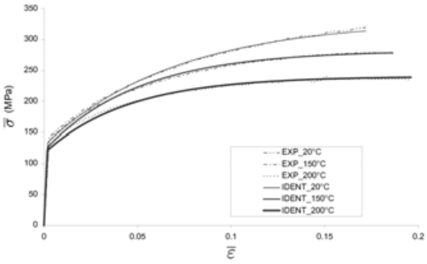


Fig.3. Flow stresses correlation results with Voce model under different temperatures and 1mm·s^{-1}

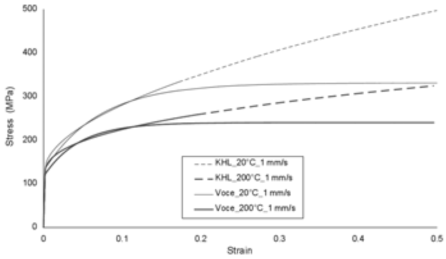


Fig.4. Flow stresses comparison predicted by Voce and KHL models with strain level up level up to 50%

Conclusion

In this work, two different types of hardening models are proposed to describe the flow stresses of AA5086 under a wide range of temperatures and strain rates. Although with a simplistic formulation, both models give good correlation results within the measured strain range while big discrepancy appears at high strain level. Special attentions should be paid in choosing the hardening law in sheet metal simulation field. Despite its advantage, the uniaxial tensile test is unable to characterize the material behaviour at high strains. An alternative method to determine the high strain level stress-strain curve is essential to identify the hardening law parameters.

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